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Research Report No. EM-166

A NOTE ON THE EXPANSION COEFFICIENT OF GEOMETRICAL OPTICS

MORRIS KLINE

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NEW YORK UNIVERSITY
Institute of Mathematical Sciences
Division of Electromagnetic Research

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Abstract

The expansion coefficient of geometrical optics is a measure of the cross section of a tube of rays and has the physical significance of measuring the intensity of the light propagating along the tube. Strictly, it is a point concept and measures the intensity along an individual ray.

This paper presents a convenient expression for the expansion coefficient. The mathematics involved is merely an application of known differential geometry but the expression derived seems to be new and is apparently unknown to workers in electromagnetic theory. The new feature of this paper is that the formula given for the variation of the expansion coefficient holds in inhomogeneous isotropic media and reduces immediately to the widely known expression for the expansion coefficient in homogeneous media, which involves the Gauss curvature of the wave front.

Table of Contents

	Page
Introduction	1
Derivation of the Fundamental Result for K(s)	3
The Expansion Coefficient for a Homogeneous Medium	10
Footnotes	11
Bibliography	12

Introduction

In geometrical optics the concept of the expansion coefficient of a tube of rays proves to be useful. Geometrically, the concept has the following meaning. One deals with a family of wave fronts, $\psi(x,y,z) = ct$, such that at time t, the corresponding surface of the family represents the location of the light.* In isotropic media, homogeneous or inhomogeneous, the family of orthogonal trajectories to the family of wave fronts is the family of rays of geometrical optics. A narrow tube of these rays, then, cuts out a small element of surface dw_1 on, say, the surface $\psi = ct_1$ and an element of surface dw_2 on, say, the surface $\psi = ct_2$. The expansion coefficient is then usually loosely defined as a function K such that

$$(1) \qquad K_1 dw_1 = K_2 dw_2$$

where K_1 and K_2 denote the values of K at the respective surfaces. (A more precise definition will be given later.) The usefulness of the function K lies in the fact that it measures the expansion or contraction of a tube of rays and indirectly the intensity or the square of the amplitude (if one treats light as a scalar disturbance) of the light propagating along the rays, for one can show[1] that if I is the intensity of the light, then

$$I_1 dw_1 = I_2 dw_2$$

where I_1 and I_2 are the intensities on the respective surfaces.

The objective of this paper is to derive a useful form for the function K as a function of s, s being arc length along a ray measured from any convenient initial point on the ray. The form to be derived, namely,

$$(2) \qquad K(s) = K(s_o)\, e^{-\int_{s_o}^{s}\left(\frac{1}{R_1(s)}+\frac{1}{R_2(s)}\right) ds} ,$$

where R_1 and R_2 are the principal radii of curvature of the wave front at the point where the ray cuts it, holds in inhomogeneous isotropic media. As will be shown, it reduces to the well-known form[2]

$$(3) \qquad K(s) = \frac{\text{const}}{R_1(s)\, R_2(s)}$$

which holds in homogeneous isotropic media.

The derivation of (2) does not require any new mathematical result but in fact is merely an application of some results in differential geometry relating to families of surfaces. Much of what follows is a simplification using ordinary vector analysis of some differential geometry to be found in tensor analysis form.[3] The reduction of (2) to (3) is also a simple consequence of a fact of differential geometry. Though the mathematics is not new, the useful form (2) for the expansion coefficient in inhomogeneous media does not seem to be known. Also the consequence (3) is here derived more rigorously as opposed to intuitive arguments usually given.

Derivation of the Fundamental Result for K(s)

We start with the family of wave fronts $\psi(x_1,x_2,x_3) = ct$ and the corresponding family of orthogonal trajectories, the rays. At any point along a ray we may introduce the usual orthogonal triple of unit vectors, the tangent, principal normal and binormal which we denote by $\underline{t}$, $\underline{n}$ and $\underline{b}$. The tangent vector to the ray is, of course, the normal to the wave front through that point and the principal normal and binormal of the ray are tangential to the wave front. For any space curve the Serret-Frenet formulas apply. Of these we need only the first one, namely,

$$(4) \qquad \underline{t}' = \kappa\underline{n} \quad ,$$

wherein κ is the curvature of the curve and where the derivative is with respect to arc-length along the curve.

We shall denote the components of any vector by subscripts; thus the components of $\underline{t}$ are (t_1,t_2,t_3). Any ray of the family is represented by $\underline{x}(s) = \left\{x_1(s),x_2(s),x_3(s)\right\}$. For each s the x_1,x_2 and x_3 of a point on a ray lies on some member of the family $\psi(x_1,x_2,x_3) = ct$.

Now

$$t_i'(s) = \frac{\partial t_i}{\partial x_j}\frac{dx_j}{ds} = \frac{\partial t_i}{\partial x_j} t_j$$

wherein summation over j is understood. Hence

$$t_i' = \underline{t} \cdot \text{grad } t_i \ .$$

Then the first Serret-Frenet formula can be written in the component form

$$(5) \qquad \underline{t} \cdot \text{grad } t_i = \kappa n_i , \qquad i = 1,2,3.$$

The common construction of the vectors $\underline{t}$, $\underline{n}$, and $\underline{b}$ gives the fact that

$$\underline{t} = \underline{n} \times \underline{b} .$$

Then, by a standard vector theorem,

$$\text{div } \underline{t} = \underline{b} \cdot \text{curl } \underline{n} - \underline{n} \cdot \text{curl } \underline{b} .$$

Since

$$\underline{b} = \underline{t} \times \underline{n} \quad \text{and} \quad \underline{n} = \underline{b} \times \underline{t} ,$$

$$\text{div } \underline{t} = (\underline{t} \times \underline{n}) \cdot \text{curl } \underline{n} - (\underline{b} \times \underline{t}) \cdot \text{curl } \underline{b}$$

$$(6) \qquad = \underline{t} \cdot \underline{n} \times \text{curl } \underline{n} + \underline{t} \cdot \underline{b} \times \text{curl } \underline{b} .$$

It is a purely algebraic, easily verifiable identity that

$$\underline{n} \times \text{curl } \underline{n} = \left(\underline{n} \cdot \frac{\partial \underline{n}}{\partial x_1} , \underline{n} \cdot \frac{\partial \underline{n}}{\partial x_2} , \underline{n} \cdot \frac{\partial \underline{n}}{\partial x_3} \right) - \left(\underline{n} \cdot \text{grad } n_1 , \underline{n} \cdot \text{grad } n_2 , n \cdot \text{grad } n_3 \right) .$$

However $\underline{n} \cdot \underline{n} = 1$ and so each of the terms in the first parenthesis is 0. Then

$$(7) \qquad \underline{n} \times \text{curl } \underline{n} = -\underline{n} \cdot (\text{grad } n_1 , \text{grad } n_2 , \text{grad } n_3) .$$

Comparison of the right side of (7) with the Serret-Frenet formula (5) shows that it is the negative of the curvature times the unit principal normal of curve C whose tangent is $\underline{n}$. This curve passes through the point P on the wave front and its tangent is the principal normal of the ray through P (fig. 1). Such a curve is not necessarily a normal section of the wave front and a fortiori not necessarily a normal section containing a principal curvature. The unit principal normal to this curve is therefore not necessarily normal to the surface. We shall denote the curvature of this curve C by κ_C and the unit principal normal to the curve by $\underline{n}_C$. Then

$$(8) \qquad \underline{n} \times \operatorname{curl} \underline{n} = -\kappa_C \, \underline{n}_C \, .$$

We may now repeat the steps for $\underline{b} \times \operatorname{curl} \underline{b}$ which we performed for $\underline{n} \times \operatorname{curl} \underline{n}$ and conclude, for the curve D through the point P on the wave front whose tangent is the binormal $\underline{b}$ of the ray through P, that

$$(9) \qquad \underline{b} \times \operatorname{curl} \underline{b} = -\kappa_D \, \underline{n}_D \, ,$$

where κ_D is the curvature of the curve D at P and $\underline{n}_D$ is the principal normal of the curve D.

If we now return to (6) and use (8) and (9) we have

$$(10) \qquad \operatorname{div} \underline{t} = -\underline{t} \cdot (\kappa_C \, \underline{n}_C + \kappa_D \, \underline{n}_D) \, .$$

We consider next a normal section to the wave front and through P and the tangent to the curve C (which is the principal normal $\underline{n}$ of the ray).

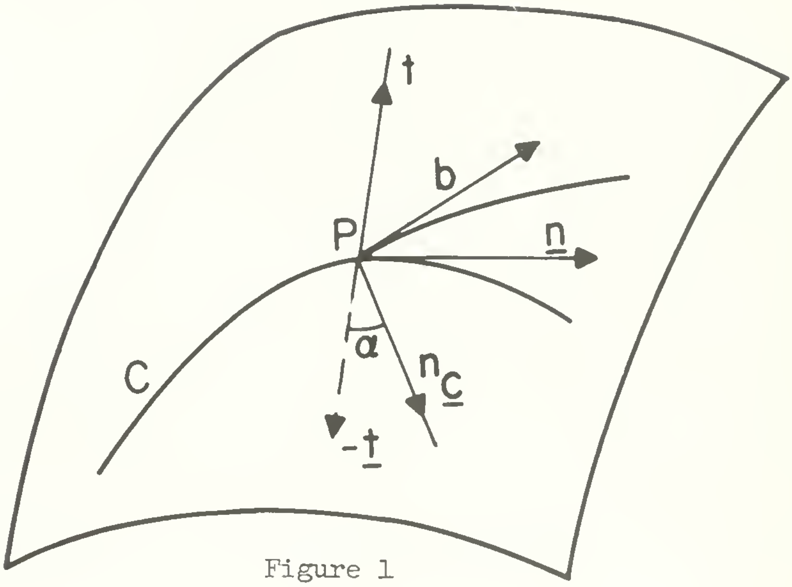

Figure 1

If k_1 is the curvature of the normal section and if its principal normal, which is $-\underline{t}$, makes an angle α with $\underline{n}_C$ then Meusnier's theorem[4] states that

$$\kappa_C \cos\alpha = k_1 .$$

Likewise, for the curve D we have

$$\kappa_D \cos\beta = k_2 ,$$

where k_2 is the curvature of the normal section through $\underline{b}$ at P.

By our choice of α and β we have that $-t \cdot \underline{n}_C = \cos\alpha$ and $-\underline{t} \cdot \underline{n}_D$ is cos β. Then from (10) we have

$$\operatorname{div} \underline{t} = k_1 + k_2 .$$

Now k_1 and k_2 are the curvatures of two normal sections, one through $\underline{n}$ and one through $\underline{b}$. Since $\underline{n}$ and $\underline{b}$ are perpendicular to each other, so are the two normal sections. It is a theorem of differential geometry that the sum of the curvatures of any two perpendicular normal sections is also the sum of the two principal curvatures.[5] If we denote the principal radii of curvature by R_1 and R_2 then $k_1 + k_2 = 1/R_1 + 1/R_2$ and

$$(11) \qquad \text{div}\ \underline{t} = \frac{1}{R_1} + \frac{1}{R_2} \ .$$

The sum on the right is twice what is called the mean curvature of the surface at the point P.

We now use the invariant definition of divergence to obtain an alternative expression for div $\underline{t}$. We have that

$$(12) \qquad \text{div}\ \underline{t} = \lim_{V \to 0} \frac{1}{V} \int_W \underline{t} \cdot \underline{n}\ dw \ .$$

Here V is the volume of a small region enclosing the point P at which the divergence is to be taken and W is the boundary of the region. The normal $\underline{n}$ to W points outward from V. We choose as our region V a tube of rays (fig. 2) bounded at each end by a small element w_1 and w_2, respectively, of the wave front surfaces. By the usual argument for the evaluation of the surface integral, we have that it is $w_2 - w_1$.

Let s be arc length along the ray through P measured from any convenient

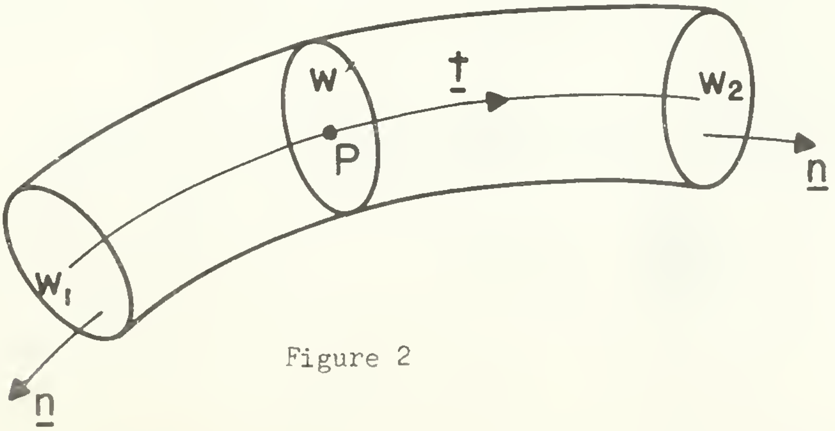

Figure 2

point on the ray. Along this tube of rays the portion of the wave front of each of the continuous family of fronts cut out by the tube is a function of s. That is, the cross section w is a function of s. Consider, in particular, the w(s) which contains P. Then

$$w_2 = w(s) + \frac{\Delta w}{\Delta s} \Delta s + \text{terms of higher order in } \Delta s \,;$$

$$w_1 = w(s) - \frac{\Delta w}{\Delta s} \Delta s + \text{terms of higher order in } \Delta s.$$

The volume V of the tube is $2\Delta w \Delta s$ + some correction term which approaches 0 with Δs. Then from (12) we have

$$(13) \qquad \operatorname{div} \underline{t} = \lim_{\substack{\Delta s \to 0 \\ w \to 0}} \frac{\frac{\Delta w}{\Delta s}}{w} \,,$$

wherein we have not written terms which are of higher order in Δs. Now, as Δs and w approach zero so that w contracts to the point P in its interior, the limit obtained will be a function of the coordinates (x_1,x_2,x_3) of P and of s, the parameter of P on the ray which goes through (x_1,x_2,x_3). We shall suppress the dependence on (x_1,x_2,x_3) because we are interested only in the variation with s. Then, from (13),

$$(14) \qquad \operatorname{div} \underline{t} = F(s) \,.$$

We may introduce a function K(s) defined by the relation

$$\frac{\frac{dK(s)}{ds}}{K(s)} = F(s) \quad ;$$

that is, K(s) is defined up to an initial value.

From observation of

$$\frac{\frac{dK(s)}{ds}}{K(s)} = \lim_{\substack{\Delta s \to 0 \\ w \to 0}} \frac{\frac{\Delta w}{\Delta s}}{w} ,$$

we see that K(s) is approximately proportional to w(s), or that, approximately,

$$\frac{K(s_2)}{K(s_1)} = \frac{w(s_2)}{w(s_1)}$$

when w(s) is a small surface element of the wave front.

It is more convenient in applications to use the reciprocal of the K(s) thus far introduced. Hence we take as the definition

$$\frac{\frac{dK(s)}{ds}}{K(s)} = -F(s) = -\text{div}\ \underline{t} .$$

Then

$$K(s) = K(s_o)\, e^{-\int_{s_o}^{s} \text{div}\ \underline{t}\ ds}$$

where s_o is some point on the ray at which the initial value of K(s) must be prescribed. In view of (11)

$$\text{(15)} \qquad K(s) = K(s_o)\, e^{-\int_{s_o}^{s} \left(\frac{1}{R_1} + \frac{1}{R_2}\right) ds}$$

Thus the expansion coefficient is obtained in terms of the mean curvature of the wave front.

The Expansion Coefficient for a Homogeneous Medium

We can now show at once that the expansion coefficient reduces to the familiar expression in terms of Gauss curvature when the medium is homogeneous. In this case the rays or the family or orthogonal trajectories to the family of wave fronts are known from geometrical optics to be straight lines. Also the wave fronts form a family of parallel surfaces, that is, the distance along each normal from one surface of the family to another, is constant.[6] However, for two parallel surfaces the principal radii of curvature lie along the same normal and

$$R_1' = R_1 + s \qquad\qquad R_2' = R_2 + s$$

where R_1' and R_2' are the principal radii of curvature on the parallel surface and s is the constant difference between the surfaces.[7]

Hence

$$\frac{dR_1}{ds} = 1 \qquad \text{and} \qquad \frac{dR_2}{ds} = 1 \,.$$

We may therefore write in place of (15)

$$(16) \qquad K(s) = K(s_o)\, e^{-\int_{s_o}^{s} \left(\frac{\frac{dR_1}{ds}}{R_1} + \frac{\frac{dR_2}{ds}}{R_2} \right) ds}$$

$$= K(s_o)\, e^{-(\log R_1(s) + \log R_2(s)) + (\log R_1(s_o) + \log R_2(s_o))}$$

$$= K(s_o) \frac{R_1(s_o)R_2(s_o)}{R_1(s)R_2(s)} = \frac{\text{const.}}{R_1(s)R_2(s)} \quad .$$

This is the familiar form of the expansion coefficient for homogeneous media.

FOOTNOTES

[*] It does not matter for our purposes whether one considers the light to be a single disturbance which at time t has reached the surface $\psi = ct$ and moves with $\psi = ct$ as t increases (Huyghens' viewpoint) or a continuing phenomenon which has a definite amplitude on $\psi = ct$ and whose amplitude changes as t changes - that is, as one passes from one surface of the fixed family to another surface.

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3. Duschek, A. and Hochrainer, A.: Grundzüge der Tensorrechnung in analytischer Darstellung, Springer Verlag, Wien, 1950, Teil II, p. 184 ff.

4. Struik, D. J.: Differential Geometry, Addison-Wesley Pub. Co., Reading, 1950, p. 76. The matter of signs may need comment. If the sense of the principal normal to a curve is chosen to be $\underline{t}'$, see (4), then the curvature is positive. Thus κ, κ_C and κ_D are positive. By choosing α and β to be the angles which $\underline{n}_C$ and $\underline{n}_D$ make with $-\underline{t}$, then both α and β are acute at an elliptic point when our $\underline{t}$, the normal to the surface, points from the concave to the convex. One value, α or β, may be obtuse if P is a hyperbolic point. In this case k_1 or k_2 is negative.

5. Struik, loc. cit., p. 81.

6. Born, M. and Wolf, E., loc. cit., p. 114.

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